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In-situ Observation of Sub-cooled Nucleate Boiling Phenomenon on Fuel Cladding Surface in High-temperature Pressurized Water using Acoustic Emission Method

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1. Introduction

Fuel crud is a corrosion product deposits on nuclear fuel cladding surface. It has often led a lot of problems such as fuel cladding corrosion, power distortion and reduction, and radio-activity build-up of out-of core. The corrosion products are dissolved out from the primary system surface and migrated with coolant flow into reactor core. They are deposited on the fuel cladding surface and partially re-released into coolant after activated by neutron absorption. The porous crud formed on fuel clad serves as the hideout for boron accumulation and results the axial power offset anomaly (AOA) due to anomalous neutron absorption [1,2]. In general, it is well known that porous crud deposition is accelerated by sub-cooled nucleate boiling (SNB) with sufficient corrosion product supply. Thereby, many researchers have had an attention on boiling dynamics including SNB and made much achievement based on thermal-hydraulic analysis and computational modeling [2-3]. However, many problems still remain to be studied for the realization of a comprehensive understanding.

The boiling dynamics of water have been well defined by many researchers with reliable boiling curve. The water begins to be boiled after bulk temperature rise up to onset nucleate boiling heat flux and film boiling occurs when the temperature reaches to critical heat flux (CHF). The bubble evolution is occurred in the extra heat difference range between onset nucleate boiling and CHF. The SNB occurs when the temperature of the coolant immediately adjacent to the heated element surface slightly exceeds the equilibrium saturation temperature. Then, bubbles from on preferred surface sites of the heated element due to local superheat conditions but those are departure and shortly collapsed by heat exchange with coolant. The boiling dynamics have been experimentally investigated with various analyzing tools such as high-speed video camera, infrared thermometry and laser interferometry at low system pressure and water temperature [3-6]. However, it is very difficult to observe bubble dynamics under high-temperature pressurized water such as nuclear primary water condition.

In this work, we observed the boiling process in high-temperature primary water using acoustic emission (AE) technique and extracted only boiling signals from AE signals by frequency filtering method. AE signals at high-temperature pressurized water were analyzed qualitatively by comparison with those obtained at atmospheric pressure, which are defined by AE signals and visualized bubble dynamics.

2. Experimental

To investigate the correlation between the visualized bubble dynamics and AE signals, the AE analysis was conducted in water pool filled in glass cell. The coolant water was made by dissolving 3.5ppm Li and 1500ppm B in deionized water. In addition, the internal heater was mounted into fuel clad as a heating element with heat capacity of max (80 W/cm^2). AE signals were observed using R3a piezo-electric sensor specialized at the frequency range of 0 to 100 kHz. The background noises of surroundings were minimized using band-pass filter and the meaningful signals were amplified by preamplifier. The AE data were processed using AE-win software in various parameters such as energy, frequency, rise time and amplitude. In addition, the AE signals were observed on the heater-inserted fuel clad surface mounted into simulated primary circulation water loop as shown in Fig. 1. Then, the coolant water chemistry is the same with that at atmospheric pressure and the bulk coolant temperature and pressure were controlled with 325^{o}C and 130 kgf/cm^2, respectively. The internal heater temperature was varied at the range of 110-200^{o}C at atmospheric pressure and 320-420^{o}C at 130 kgf/cm^2, respectively, which include the saturated equilibrium temperature at each pressure.

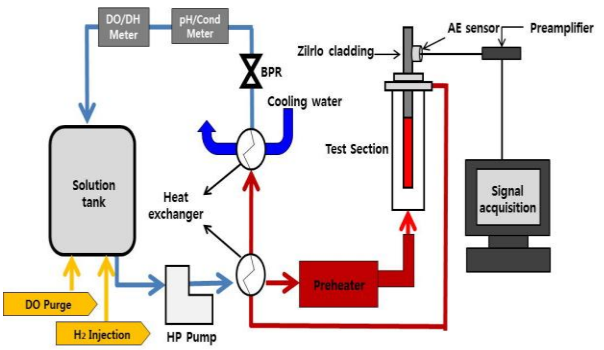

Fig. 1 Schematic drawing of the primary simulation loop and AE system.

2. Results and discussion

Fig. 2 shows the average frequency of the AE signals obtained in a glass cell at atmospheric pressure. When the internal heater temperature decreased from 200^{o}C to 110^{o}C, the coolant temperature was varied from 101.5°C to 95°C. The signals in the frequency range of 11-40 kHz was occurred homogeneously over the full heating range. Therefore, the signals in this range were considered to be noise from the internal heater. Consequently, the signals in both range of 41-100 kHz and 1-10 kHz should be boiling signals. That is, SNB signals were observed at the internal heater temperatures above 130°C.

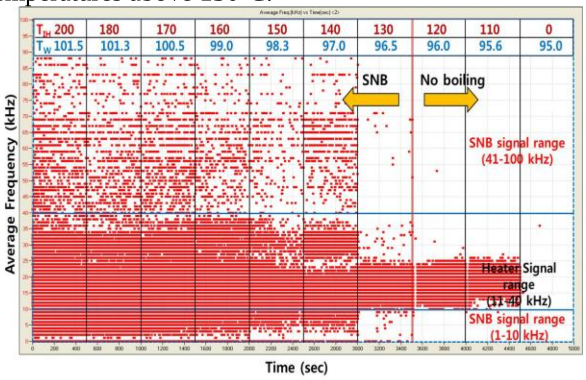

Fig. 2 AE signals in terms of average frequency as a function of internal heater temperature at atmospheric pressure condition.

Fig. 3 shows the AE signals in terms of absolute energy after removing the heater signals in frequency range of 11-40 kHz to extract only boiling signals. The AE energy was spread in an energy span of 20-600 aJ but displayed the decrease in event as the internal heater temperature decreases. In addition, the high energy level events decreased as the internal heater temperature decreased.

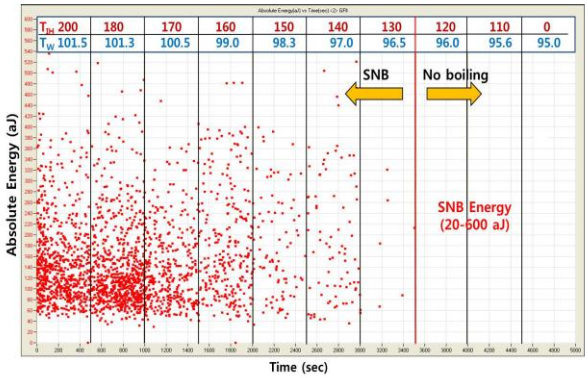

Fig. 3 SNB signals in the absolute energy after the removal of internal heater noise signals at atmosphere pressure condition.

To determine the AE signals for the SNB at high-temperature pressurized water, AE signals associated with the boiling dynamics were extracted by the removal of heater signals through the same frequency filtering procedure used at atmosphere pressure. Fig. 4 shows AE signals in the absolute energy after removing heater signals. The boiling AE signals were observed at the internal heater temperatures higher than 380°C. The AE energy for boiling ranged from 120 to 340 aJ, which is relatively low energy level compared to that at atmospheric pressure as shown in Fig. 3. In addition, the number of signals was dramatically decreased than that at atmospheric pressure

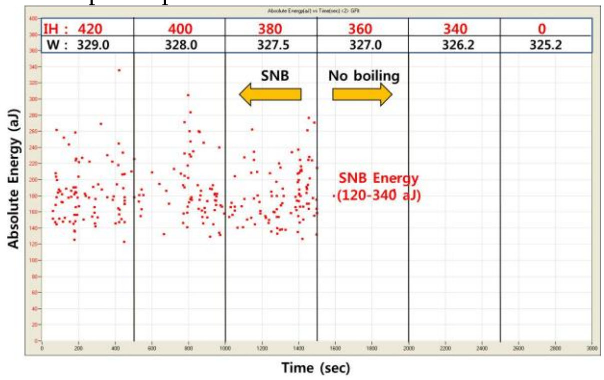

Fig. 4 SNB signals in the absolute energy after the removal of internal heater noise signals at 130 kgf/cm^2.

4. Conclusions

We successfully observed the boiling process at atmospheric pressure and high-temperature pressure using AE analysis method. The boiling signals were extracted through frequency filtering process. Furthermore, the boiling dynamics were qualitatively understood from the correlation between the visualized bubble dynamics and AE signals. As a result, the boiling signals were observed under internal heater temperature over 380°C in bulk water around 328°C at 130kgf/cm^2. Moreover, the AE energy was distributed in the range of 20-600J with two frequency regions of 1-10 kHz and 41-100kHz and shows relatively small events at low energy comparing to that at atmospheric pressure. It indicates that the boiling bubble density decreased and its energy declined due to increase of system pressure.

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Acknowledgments

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